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Zirconium-Doped Zinc Oxide Nanoparticles: Synthesis, Structural Characteristics, Physicochemical Properties and Emerging Applications

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Abstract

Zirconium-doped zinc oxide (Zr–ZnO) nanoparticles have emerged as promising multifunctional semiconductor nanomaterials because zirconium incorporation can modify the structural, optical, electrical, surface and catalytic characteristics of ZnO. Zinc oxide possesses a wide direct band gap, high exciton binding energy, chemical stability and diverse nanoscale morphologies, making it suitable for photocatalysis, antimicrobial materials, sensing, optoelectronics and environmental applications. However, the functional performance of pristine ZnO is influenced by charge-carrier recombination, defect concentration, particle aggregation and limited visible-light utilization. Elemental doping provides an effective strategy for modifying these characteristics. Among different dopants, zirconium is particularly interesting because of its ability to alter lattice structure, defect chemistry, carrier behavior and surface properties. This article reviews the reported synthesis strategies, structural characteristics, physicochemical properties and emerging applications of Zr-doped ZnO nanoparticles. Sol–gel, precipitation, hydrothermal and combustion-assisted approaches are discussed in relation to particle size, crystallinity, morphology and dopant incorporation. X-ray diffraction, electron microscopy, energy-dispersive spectroscopy, Fourier-transform infrared spectroscopy, Raman spectroscopy, X-ray photoelectron spectroscopy, UV–visible spectroscopy and photoluminescence are considered as complementary characterization approaches. Particular attention is given to concentration-dependent changes in crystallite size, lattice parameters, optical band gap, defect states, surface characteristics, electrochemical response and photocatalytic performance. Published evidence indicates that controlled Zr incorporation can retain the hexagonal wurtzite structure while modifying the physicochemical characteristics of ZnO. Zr–ZnO nanoparticles have demonstrated potential in photocatalytic water treatment, antibacterial materials and electrochemical sensing, while related Zr-doped ZnO nanostructures have also been investigated for transparent conducting and photovoltaic applications. The review identifies current limitations related to dopant distribution, concentration optimization, reproducibility, scalability and safety and proposes future research directions for application-specific Zr–ZnO nanomaterials.

1. Introduction

Nanostructured metal oxides have become important functional materials because their properties can be controlled through composition, crystallinity, morphology, particle size, surface area and defect concentration. Among semiconductor metal oxides, zinc oxide (ZnO) has attracted substantial scientific interest because of its wide direct band gap of approximately 3.37 eV, high exciton binding energy and combination of optical, electrical, piezoelectric, catalytic and chemical properties (Özgür *et al.*, 2005; Janotti and Van de Walle, 2009). These characteristics have resulted in the investigation of ZnO for ultraviolet optoelectronics, sensors, photocatalysis, energy conversion, antimicrobial systems and environmental remediation.

ZnO generally crystallizes in the hexagonal wurtzite structure under ambient conditions. The non-centrosymmetric structure contributes to its piezoelectric behavior, whereas intrinsic defects such as oxygen vacancies, zinc vacancies and zinc interstitials can influence its electronic and optical characteristics (Wang, 2004; Janotti and Van de Walle, 2009). When

ZnO is produced at the nanoscale, the high surface-to-volume ratio increases the contribution of surface atoms, surface defects and interfacial reactions. Therefore, nanoparticle size, aggregation, morphology and surface chemistry are important determinants of its functional performance.

A major limitation of pristine ZnO in photocatalytic applications is rapid recombination of photogenerated electron–hole pairs. In addition, its relatively wide band gap limits strong absorption mainly to the ultraviolet region. Doping with suitable elements can modify the electronic structure and defect chemistry of ZnO and can consequently influence light absorption, carrier separation and surface reactivity. Reviews of doped ZnO nanostructures have emphasized that the preparation method, crystal morphology and particle size strongly influence the resulting structural and optical properties.

Zirconium is an attractive dopant because Zr^{4+} differs from Zn^{2+} in valence and ionic characteristics. Incorporation of Zr can therefore introduce lattice distortion and associated charge-compensation effects. Depending on concentration and synthesis conditions, Zr may influence crystallite growth, defect formation, carrier concentration, optical transitions and surface activity.

Naik *et al.,* (2020) prepared $Zn_{1}{-}xZr_{x}O$ nanoparticles with x = 0, 0.01, 0.03 and 0.05 using a sol–gel route. The study employed XRD, FTIR, FESEM, TEM, UV–visible and photoluminescence techniques and reported changes in structural and optical properties following Zr incorporation. The Zr-doped nanoparticles also showed improved antibacterial activity and enhanced electrochemical performance toward uric-acid detection compared with pristine ZnO.

The environmental applications of Zr–ZnO have also attracted attention. A hydrothermal study investigated Zr-doped ZnO nanoparticles for degradation of trihalomethanes in water and reported removal efficiencies of 79.25% for bromoform, 96.5% for bromomethane chloride, 65% for dichlorobromomethane and 52% for total trihalomethanes under the optimum UV conditions. The same study reported approximately 42% higher photocatalytic efficiency for Zr–ZnO compared with bare ZnO. More recently, Gouthamsri *et al.,* (2023) synthesized Zr-doped ZnO through a glycine-assisted sol–gel/combustion approach. The reported Zr–ZnO nanohybrid had an average particle size of approximately 18 nm compared with 24 nm for pure ZnO and achieved complete degradation of Crystal Violet under the reported visible-light conditions within 90 min. The material also demonstrated antibacterial activity against *Vibrio cholerae* and *Clostridium perfringens*.

Zr-containing ZnO systems have also been investigated beyond photocatalysis. Studies of Zr-doped ZnO films have examined their optical and electrical characteristics for transparent conducting applications, while Zr-modified ZnO nanoparticles have been investigated as interfacial materials in photovoltaic devices and as potential biomedical materials.

Despite these developments, the reported effects of Zr doping are not always identical. Some studies report changes toward lower band-gap values, whereas others observe a blue shift. Such differences can arise from variations in dopant concentration, synthesis method, crystallite size, lattice strain, defect concentration and carrier density. Therefore, the influence of Zr should be considered as a combined structural and electronic effect rather than as a simple concentration-dependent phenomenon.

The objective of this review is to critically summarize the synthesis, structural characteristics, physicochemical properties and emerging applications of Zr-doped ZnO nanoparticles. Particular attention is given to the relationship between Zr concentration, structure, defects and functional properties.

Table 1. Fundamental characteristics of ZnO relevant to zirconium doping

Property	**Characteristic**	**Importance**
Crystal structure	Hexagonal wurtzite	Provides structural framework for Zr

		incorporation
Band gap	~3.37 eV	Determines optical absorption
Exciton binding energy	~60 meV	Important for room-temperature optical behavior
Surface area	Increases at nanoscale	Enhances adsorption and catalytic reactions
Defects	Oxygen vacancies, Zn-related defects	Influence optical/electrical properties
Semiconductor behavior	n-type	Important for sensing and optoelectronic applications
Piezoelectricity	Present in wurtzite ZnO	Enables multifunctional applications

2. Zirconium Doping and Modification of ZnO

Zr doping can modify ZnO through changes in lattice structure and electronic states. The higher valence of Zr relative to Zn can influence charge compensation and defect formation. The actual effect depends strongly on whether Zr occupies substitutional lattice sites, resides at grain boundaries or forms separate Zr-containing phases.

Experimental studies generally indicate that moderate Zr concentrations can be incorporated without destroying the ZnO wurtzite structure. However, excessive incorporation can introduce structural disorder and may eventually result in secondary phases.

An important feature of Zr doping is the possibility of modifying oxygen-vacancy populations. Defects can act as charge traps and may either enhance or suppress photocatalytic activity depending on their concentration and energetic position. Consequently, an optimum Zr concentration may exist at which charge separation and surface reactions are enhanced without excessive recombination.

The effect is also morphology-dependent. Smaller Zr–ZnO nanoparticles provide larger specific surface area and may expose more active sites, whereas excessive aggregation can decrease the accessible surface area.

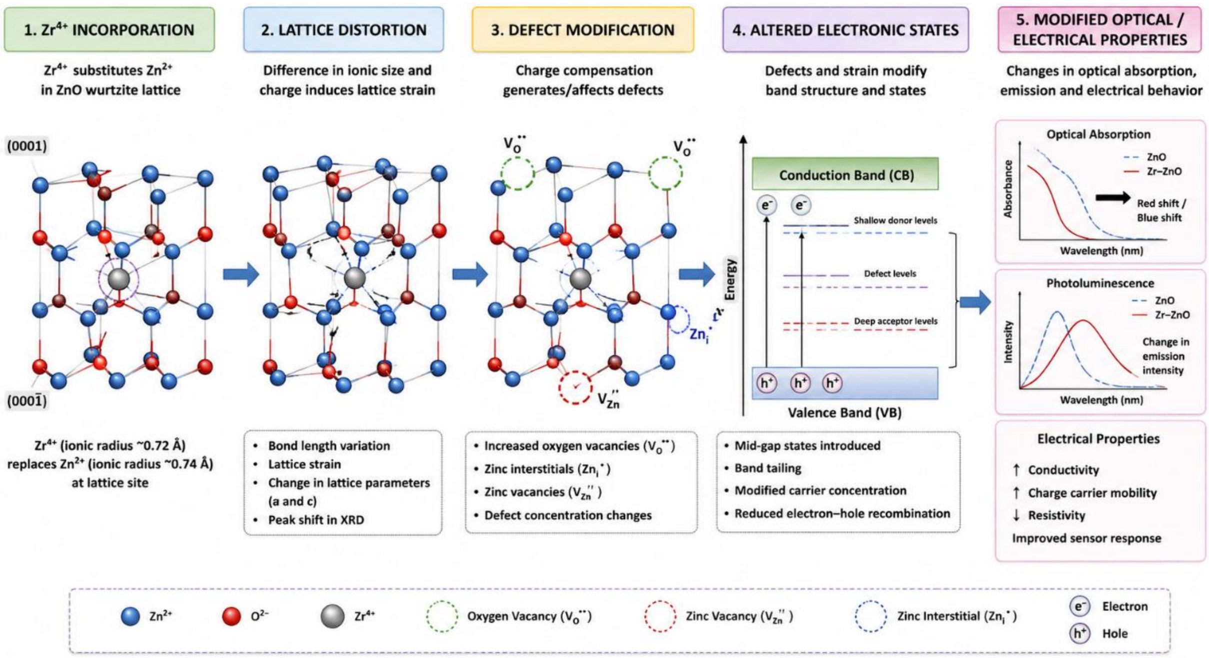


Figure 1. Schematic representation of Zr incorporation into the ZnO wurtzite lattice and its influence on lattice distortion, defects and electronic structure.

3. Synthesis of Zr-Doped ZnO Nanoparticles

3.1 Sol–Gel Method

Sol–gel processing is among the most frequently used approaches for preparing Zr-doped ZnO nanoparticles. Zinc and zirconium precursors are dissolved in a suitable solvent, followed by hydrolysis, condensation, gel formation, drying and thermal treatment.

A major advantage is the possibility of controlling the nominal dopant concentration through precursor ratios. Naik *et al.,* (2020) used this method to prepare $Zn_{1-x}Zr_xO$ nanoparticles containing 0–5% Zr and subsequently investigated their structural, optical, electrochemical and antibacterial properties.

Gouthamsri *et al.,* (2023) combined sol–gel processing with combustion using glycine as fuel. The approach produced a Zr–ZnO nanohybrid with smaller reported particle size than pure ZnO and demonstrated both photocatalytic and antibacterial performance.

3.2 Precipitation

Precipitation is relatively simple, economical and potentially suitable for scale-up. Metal precursor solutions are converted into hydroxide or carbonate intermediates, followed by washing, drying and calcination.

The main limitation is that uncontrolled nucleation can produce broad particle-size distributions and aggregation. Parameters such as pH, precursor concentration, temperature and precipitation rate therefore require careful optimization.

3.3 Hydrothermal Method

Hydrothermal processing allows crystal growth under controlled temperature and pressure. It is particularly useful for producing crystalline nanoparticles with controlled morphology.

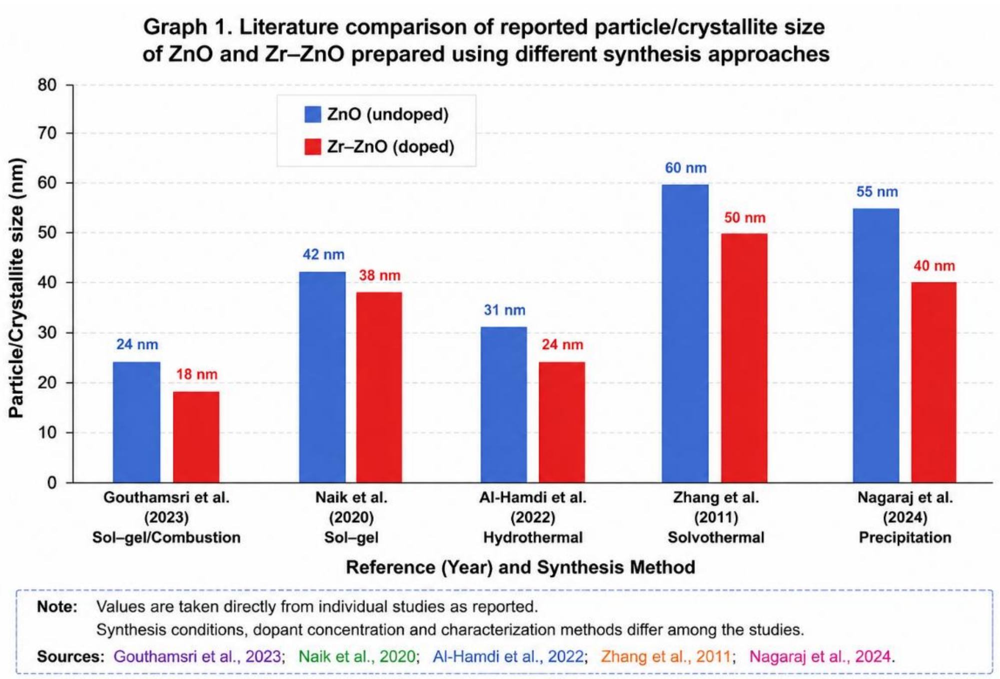
The hydrothermal Zr–ZnO study reported by Al-Hamdi *et al.,* (2022) used XRD, SEM, FTIR, dynamic light scattering and zeta-potential measurements to characterize the nanoparticles before evaluating their photocatalytic activity.

3.4 Combustion-Assisted Synthesis

Combustion-assisted synthesis can generate nanoparticles rapidly and may produce relatively small crystallites. The glycine-assisted method reported by Gouthamsri *et al.,* (2023) produced Zr–ZnO with an average size of approximately 18 nm compared with approximately 24 nm for ZnO prepared under the same study conditions.

Table 2. Comparison of reported synthesis strategies

Synthesis method	Main advantage	Major limitation	Important control parameters
Sol–gel	Good dopant-level control	Sensitive to hydrolysis and calcination	pH, precursor ratio, temperature
Precipitation	Simple and economical	Aggregation	pH, addition rate, temperature
Hydrothermal	High crystallinity	Requires pressure vessel	Temperature, time, precursor concentration
Combustion-assisted	Rapid synthesis and small particles	Possible agglomeration	Fuel/oxidant ratio, calcination
Spray-based deposition	Useful for films	Mainly coating-oriented	Substrate temperature, spray rate



Graph 1. Literature comparison of reported particle/crystallite size of ZnO and Zr–ZnO prepared using different synthesis approaches.

4. Structural and Morphological Characteristics

4.1 X-Ray Diffraction

XRD is the primary method used to identify crystalline phases and evaluate structural changes after doping. Zr-doped ZnO nanoparticles generally retain the hexagonal wurtzite structure at moderate dopant concentrations.

Naik *et al.,* (2020) reported the ZnO wurtzite phase for the investigated Zr concentrations. The absence of obvious secondary peaks suggests that the Zr levels used were sufficiently low to maintain the ZnO host structure.

However, absence of a secondary XRD peak alone cannot establish substitutional incorporation. Very low concentrations of secondary phases may remain below the detection limit.

4.2 Crystallite Size

Crystallite size is commonly estimated from XRD peak broadening using the Scherrer equation. Doping may reduce crystallite growth through inhibition of nucleation and grain growth, although the opposite behavior can occur depending on synthesis conditions.

The reported reduction from 24 nm for ZnO to 18 nm for Zr–ZnO in the glycine-assisted study is one example of Zr-associated size modification.

4.3 SEM and TEM

SEM provides information about surface morphology and aggregation, whereas TEM enables direct evaluation of particle dimensions and nanoscale morphology.

The combination of SEM and TEM is particularly useful because a single measurement cannot adequately describe both aggregate size and individual nanoparticle size.

4.4 EDS and Elemental Mapping

EDS confirms the presence of Zn, O and Zr. Elemental mapping can provide evidence for spatial distribution of Zr.

Nevertheless, EDS does not establish whether Zr occupies Zn lattice sites. XPS, XANES, EXAFS and high-resolution TEM can provide stronger evidence for chemical incorporation.

4.5 FTIR and Raman Spectroscopy

FTIR can identify Zn–O-related vibrational characteristics, whereas Raman spectroscopy is sensitive to lattice vibrations and structural disorder. Changes in peak intensity and position following doping may indicate lattice distortion and defect modification.

4.6 XPS

XPS provides surface-sensitive information about oxidation states and elemental composition. It is particularly useful for determining the chemical environment of Zr and oxygen.

Table 3. Characterization techniques and information obtained

Technique	Primary information	Relevance to Zr–ZnO
XRD	Phase and crystallinity	Wurtzite structure, lattice changes
SEM	Surface morphology	Aggregation and particle morphology
TEM	Particle size and shape	Direct nanoscale observation
EDS	Elemental composition	Confirmation of Zr
Elemental mapping	Spatial distribution	Dopant homogeneity
FTIR	Functional vibrations	Zn–O and surface interactions
Raman	Lattice vibrations	Structural disorder and defects
XPS	Surface chemistry	Zr and oxygen chemical states
UV–Vis	Absorption/band gap	Optical modification
PL	Radiative emission	Defect and recombination behavior
BET	Surface area	Adsorption and catalytic activity
DLS	Hydrodynamic size	Dispersion behavior
Zeta potential	Surface charge	Colloidal stability

5. Optical and Electronic Properties

5.1 UV–Visible Absorption

Zr incorporation can alter the absorption edge and apparent optical band gap of ZnO. Naik *et al.,* (2020) reported a shift of the absorption edge toward lower wavelength and a red-shifted band-gap response for their Zr-doped ZnO nanoparticles.

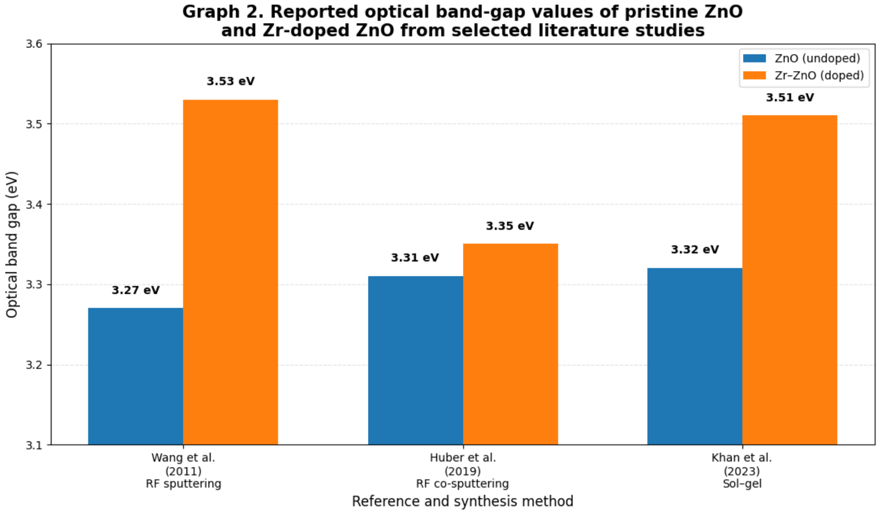
However, band-gap behavior is not universally identical across studies. Differences can result from carrier concentration, defect states, lattice strain and particle-size effects.

Therefore, comparisons should consider whether the reported value represents a fundamental band gap or an optical estimate derived from a particular Tauc-model assumption.

5.2 Photoluminescence

PL spectroscopy provides information about radiative recombination and defect-related transitions. Naik *et al.,* (2020) observed band-edge, violet, blue and green emission in their Zr-doped ZnO samples, with intensity changing with dopant concentration.

The visible PL region is commonly associated with defect-related states, but individual emission peaks should not automatically be assigned to one specific defect without supporting spectroscopic evidence.



Graph 2. Reported optical band-gap values of pristine ZnO and Zr-doped ZnO from selected literature studies.

6. Surface, Defect and Electrochemical Properties

6.1 Defect Chemistry

Defects strongly influence the behavior of ZnO nanoparticles. Oxygen vacancies may act as charge-trapping sites and can participate in photocatalytic reactions. However, excessive defects can also act as recombination centers.

Zr doping can modify the concentration and distribution of these defects. The resulting effect depends on the dopant concentration and synthesis atmosphere.

6.2 Surface Area

Surface area is particularly important for photocatalytic and adsorption applications. Smaller nanoparticles and reduced aggregation generally increase accessible surface sites.

The recent biomedical Zr–ZnO literature also suggests that Zr modification can increase specific surface area, providing an additional structural parameter for understanding biological interactions.

6.3 Electrochemical Behavior

Naik *et al.,* (2020) demonstrated that Zr doping affected the electrochemical response of ZnO toward uric acid. A Zr-doped ZnO modified carbon-paste electrode showed superior performance compared with the undoped material under the investigated conditions. This suggests that Zr–ZnO may be useful in electrochemical sensing, although more studies are needed to establish selectivity and long-term stability.

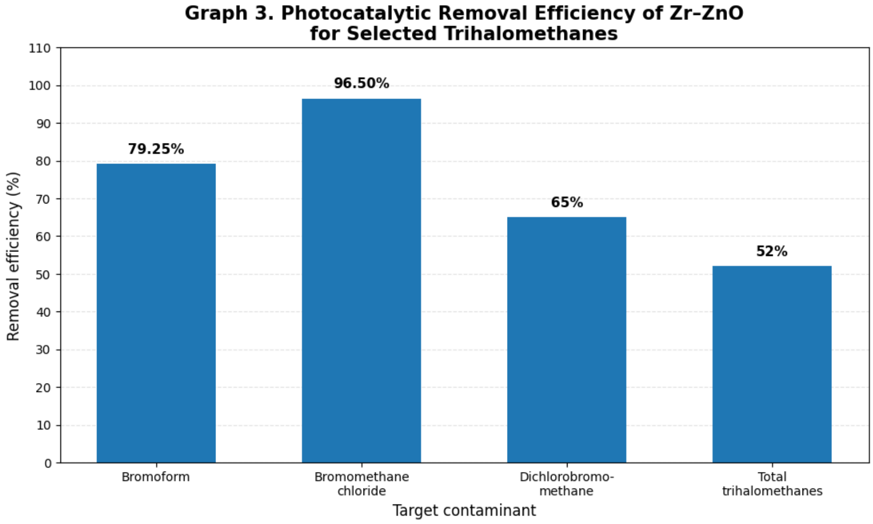
7. Photocatalytic Properties

Photocatalysis is one of the strongest application areas for Zr–ZnO.

When ZnO absorbs photons with sufficient energy, electron–hole pairs are generated. These charge carriers can migrate toward the surface and participate in reactions that produce reactive oxygen species. The resulting species can degrade organic contaminants or contribute to microbial inactivation.

Zr doping can modify this process through changes in defect states, charge separation and surface characteristics.

Al-Hamdi *et al.,* (2022) demonstrated the environmental potential of Zr–ZnO nanoparticles for degradation of trihalomethanes. Under optimum UV conditions, removal efficiencies were 79.25% for bromoform, 96.5% for bromomethane chloride, 65% for dichlorobromomethane and 52% for total trihalomethanes. Under sunlight, the reported removal values were 20%, 88.5%, 99.75%, 65% and 67%, respectively, for the listed compounds.



Graph 3. Photocatalytic removal efficiency of Zr–ZnO for selected trihalomethanes.

8. Antibacterial Properties

ZnO nanoparticles can exhibit antibacterial activity through several mechanisms, including reactive oxygen species generation, membrane interaction and release of Zn^{2+}. Doping can modify these mechanisms through changes in surface chemistry and defect concentration.

Naik *et al.,* (2020) reported improved antibacterial activity of Zr-doped ZnO against both *Bacillus subtilis* and *Klebsiella pneumoniae*.

Gouthamsri *et al.,* (2023) reported antibacterial effectiveness of Zr–ZnO against *Vibrio cholerae* and *Clostridium perfringens*.

Because antibacterial results are highly dependent on concentration, particle size, bacterial strain, exposure time and assay method, direct comparison of zone-of-inhibition values between unrelated studies should be avoided unless experimental conditions are sufficiently comparable.

Table 4. Reported functional applications of Zr–ZnO

Application	**Material characteristic involved**	**Literature evidence**
Photocatalytic water treatment	Charge separation and surface reactivity	Trihalomethane degradation
Dye degradation	Light-induced reactive species	Crystal Violet degradation
Antibacterial materials	ROS and surface interaction	Activity against Gram-positive and Gram-negative bacteria
Electrochemical sensing	Modified charge-transfer behavior	Uric-acid detection
Transparent conducting materials	Electrical conductivity + transparency	Zr-doped ZnO films
Photovoltaics	Improved charge extraction	ZnO:Zr interfacial layers

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Biomedical materials	Surface area and biological interaction	Emerging tissue-engineering research

9. Other Emerging Applications

9.1 Transparent Conducting Materials

Although thin-film studies are outside the strict nanoparticle focus, they demonstrate the broader ability of Zr to modify ZnO electrical properties. Such systems are relevant to transparent electrodes and optoelectronic devices.

9.2 Photovoltaic Devices

Zr-doped ZnO nanoparticles have been investigated as cathode interfacial layers in organic solar cells. The reported improvement in power-conversion efficiency indicates that Zr modification can influence charge extraction and recombination.

9.3 Biomedical Materials

Recent studies have begun investigating Zr–ZnO nanoparticles in tissue-engineering contexts. Increased surface area and favorable cellular responses indicate potential for biomaterial development, although extensive toxicity and long-term biocompatibility studies are still necessary.

10. Critical Comparison of Literature

Table 5. Representative studies on Zr-modified ZnO

Reference	Synthesis	Material	Main characterization	Major finding
Paul *et al.*, (2003)	Sol–gel	Zr–ZnO film	XRD, optical/electrical	Zr modified resistivity and crystallite characteristics
Gokulakrishnan *et al.*, (2011)	Spray pyrolysis	Zr–ZnO film	Structural, optical, electrical	High visible transparency and optimized resistivity
Zhang *et al.*, (2011)	Nanoparticle synthesis	Zr-doped ZnO	Structural/magnetic	Zr affected magnetic behavior
Naik *et al.*, (2020)	Sol–gel	Zr–ZnO nanoparticles	XRD, FTIR, FESEM, TEM, UV–Vis, PL	Optical, electrochemical and antibacterial improvement
Al-Hamdi *et al.*, (2022)	Hydrothermal	Zr–ZnO nanoparticles	XRD, SEM, FTIR, DLS, zeta potential	Photocatalytic water treatment
Gouthamsri *et al.*, (2023)	Sol–gel/combustion	Zr–ZnO nanohybrid	XRD, XPS, SEM, BET, TGA	Crystal Violet degradation and antibacterial activity
Nagaraj *et al.*, (2024)	Precipitation	Zr-doped ZnO	Structural/morphological	Antibacterial potential

Recent biomedical study	Continuous hydrothermal	Zr–ZnO nanoparticles	XRD, BET, biological assays	Surface-area and cellular-response potential

11. Structure–Property Relationship

The literature collectively indicates the following sequence:

Zr concentration

↓

Zr incorporation / distribution

↓

Lattice distortion + defect modification

↓

Changes in crystallite size, morphology and surface area

↓

Modified electronic structure

↓

Changes in absorption, charge separation and surface reactivity

↓

Photocatalytic + antibacterial + electrochemical performance

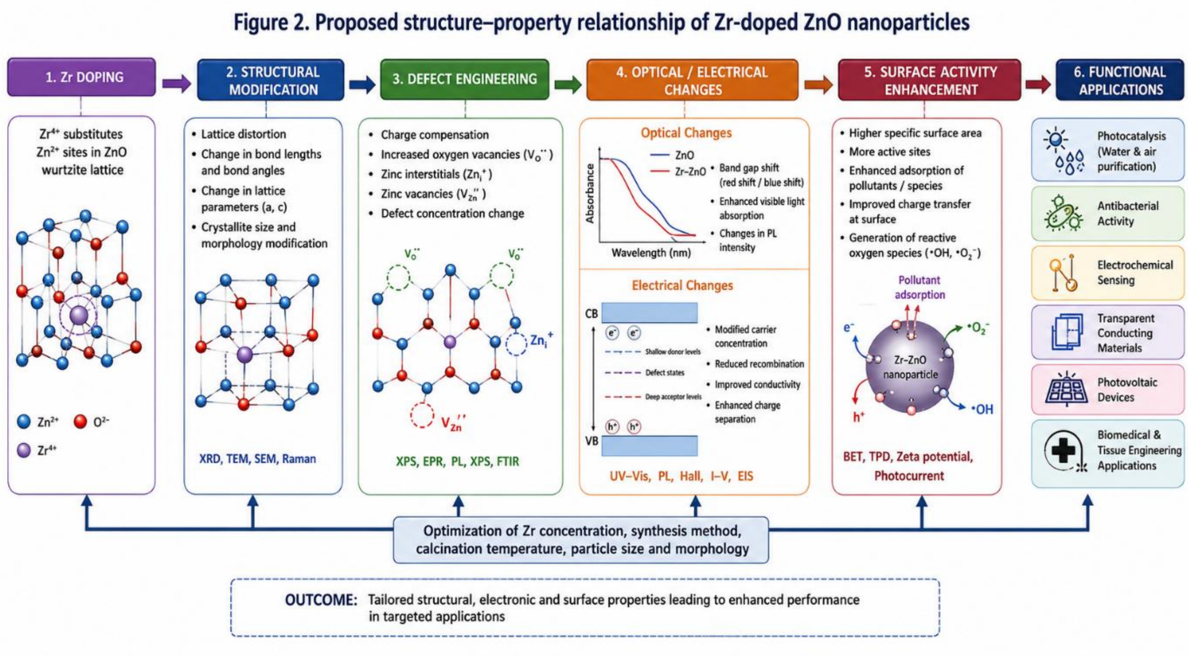

Figure 2. Proposed structure–property relationship of Zr-doped ZnO nanoparticles.

12. Challenges and Research Gaps

Despite substantial progress, several issues remain unresolved.

12.1 Dopant distribution

The presence of Zr detected by EDS does not prove substitutional incorporation. Advanced characterization should be used to determine the local chemical environment.

12.2 Optimum dopant concentration

Higher Zr concentration does not necessarily result in better performance. Excessive doping can increase structural disorder and reduce crystallinity.

12.3 Contradictory optical trends

Different studies have reported different band-gap responses. These differences should be interpreted considering particle size, strain, carrier concentration and defects.

12.4 Reproducibility

Variations in precursor chemistry, pH, calcination and reaction temperature can produce substantially different nanoparticle properties.

12.5 Scale-up

Most studies remain at laboratory scale. Continuous and environmentally sustainable synthesis routes require further development.

12.6 Safety

For environmental and biomedical applications, nanoparticle release, toxicity, biodegradation and long-term environmental fate must be systematically evaluated.

13. Future Perspectives

Future research should move beyond simple preparation and characterization toward quantitative structure–property relationships.

A particularly useful experimental framework would maintain identical synthesis conditions while systematically varying Zr concentration. Each composition should then be evaluated using XRD, XPS, TEM, BET, UV–Vis, PL and electrochemical techniques.

The development of green synthesis approaches is another promising direction. Plant-mediated or low-toxicity synthesis may reduce environmental burden, while continuous hydrothermal processing could improve scalability.

For photocatalysis, immobilized Zr–ZnO systems may provide advantages over free nanoparticle suspensions because the catalyst can be recovered more easily. Hybridization with other semiconductors, carbon-based materials or polymers could further improve charge separation.

For antibacterial applications, future studies should standardize bacterial strains, nanoparticle concentration, exposure time and assay conditions so that results can be quantitatively compared across studies.

14. Conclusion

Zirconium-doped ZnO nanoparticles represent an important class of modified semiconductor nanomaterials with promising structural, optical, surface, electrochemical, photocatalytic and antibacterial properties. The available literature demonstrates that controlled Zr incorporation can modify ZnO while retaining the characteristic wurtzite structure at appropriate concentrations.

Sol–gel, precipitation, hydrothermal and combustion-assisted routes provide different opportunities for controlling dopant distribution, particle size, crystallinity and morphology. Comprehensive characterization using XRD, SEM, TEM, EDS, FTIR, Raman, XPS, UV–Vis, PL and BET is necessary to establish reliable structure–property relationships.

Among the emerging applications, photocatalytic environmental remediation is particularly promising. Published hydrothermal Zr–ZnO nanoparticles have demonstrated substantial degradation of water disinfection by-products, while other Zr–ZnO systems have shown efficient dye degradation and antibacterial activity. Electrochemical sensing, photovoltaic devices and biomedical materials represent additional areas of growing interest.

Nevertheless, Zr–ZnO research remains limited by differences in synthesis conditions, inconsistent concentration-dependent trends and insufficient understanding of dopant location and defect chemistry. Future studies should emphasize standardized synthesis, advanced characterization, scalable production, long-term stability and comprehensive safety assessment. Establishing clear relationships between Zr concentration, structural modification and functional performance will be essential for translating Zr–ZnO nanoparticles from laboratory research into practical multifunctional technologies.

References

1. Özgür, Ü., Alivov, Y.I., Liu, C., Teke, A., Reshchikov, M.A., Doğan, S., Avrutin, V., Cho, S.J. and Morkoç, H. (2005). A comprehensive review of ZnO materials and devices. *Journal of Applied Physics*, 98, 041301.

2. Janotti, A. and Van de Walle, C.G. (2009). Fundamentals of zinc oxide as a semiconductor. *Reports on Progress in Physics*, 72, 126501.

3. Wang, Z.L. (2004). Zinc oxide nanostructures: Growth, properties and applications. *Journal of Physics: Condensed Matter*, 16, R829–R858.

4. Morkoç, H. and Özgür, Ü. (2009). *Zinc Oxide: Fundamentals, Materials and Device Technology*. Wiley-VCH, Weinheim.

5. Paul, G.K., Bandyopadhyay, S., Sen, S.K. and Sen, S. (2003). Structural, optical and electrical studies on sol-gel deposited Zr doped ZnO films. *Materials Chemistry and Physics*, 79, 71–75.

6. Gokulakrishnan, V., Parthiban, S., Jeganathan, K. and Ramamurthi, K. (2011). Investigation on the effect of Zr doping in ZnO thin films by spray pyrolysis. *Applied Surface Science*, 257, 9068–9072.

7. Zhang, J., Gao, D., Yang, G., Zhang, J., Shi, Z., Zhang, Z., Zhu, Z. and Xue, D. (2011). Synthesis and magnetic properties of Zr doped ZnO nanoparticles. *Nanoscale Research Letters*, 6, 587.

8. Naik, E.I., Naik, H.B., Viswanath, R., Kirthan, B. and Prabhakara, M. (2020). Effect of zirconium doping on the structural, optical, electrochemical and antibacterial properties of ZnO nanoparticles prepared by sol-gel method. *Chemical Data Collections*, 29, 100505.

9. Sung, N.E., Lee, K.S., Lee, I.J., *et al.*, (2018). Structural characterization of Zr-doped ZnO films deposited on quartz substrates by reactive radio frequency magnetron co-sputtering. *Thin Solid Films*, 651, 42–47.

10. Gouthamsri, S., Ramanaiah, M., Basavaiah, K. and Jaya Rao, K. (2023). Zr-doped ZnO nanohybrid via glycine mediated sol–gel approach as benign supporter for degradation of Crystal violet and antibacterial performance. *Results in Chemistry*, 6, 101080.

11. Nagaraj, K., Kaliyaperumal, R., Poovan, V.K., Al-Sadoon, M.K., Kasilingam, T. and Kumaravel, T. (2024). Zirconium-doped zinc nanocomposites (ZDZN): Preparation, characterization, and evaluation of antibacterial activity. *Journal of Inorganic and Organometallic Polymers and Materials*.

12. Srujana, B.S., Prakash, A., Chattopadhyay, S. and Mahesha, M.G. (2023). Zirconium doped zinc oxide thin films grown by spray pyrolysis technique for TCO applications. *Materials Today Communications*, 37, 107476.

13. Herodotou, S., Treharne, R.E., Durose, K., Tatlock, G.J. and Potter, R.J. (2015). The effects of Zr doping on the optical, electrical and microstructural properties of thin ZnO films deposited by atomic layer deposition. *Materials*, 8, 7230–7240.

14. Kim, H., Horwitz, J.S., Kim, W.H., Qadri, S.B. and Kafafi, Z.H. (2003). Anode material based on Zr-doped ZnO thin films for organic light-emitting diodes. *Applied Physics Letters*, 83, 3809–3811.

15. Lin, M.C., Chang, Y.J., Chen, M.J. and Chu, C.J. (2011). Characteristics of Zr-doped ZnO thin films grown by atomic layer deposition. *Journal of The Electrochemical Society*, 158, D395–D398.

16. Bahedi, K., Addou, M., Jouad, M.E., Bayoud, S. and Sofiani, Z. (2009).

Effects of deposition temperature on the surface roughness and the nonlinear optical susceptibility of sprayed deposited ZnO:Zr thin films. *Applied Surface Science*, 255, 9054–9057.

17. Selvam, N.C.S., Vijaya, J.J. and Kennedy, L.J. (2012). Effects of morphology and Zr doping on structural, optical, and photocatalytic properties of ZnO nanostructures. *Industrial & Engineering Chemistry Research*, 51, 16333–16345.

18. Subash, B., Krishnakumar, B., Swaminathan, M. and Shanthi, M. (2013). Highly efficient, solar active, and reusable photocatalyst: Zr-loaded Ag-ZnO for reactive red 120 dye degradation with synergistic effect and dye-sensitized mechanism. *Langmuir*, 29, 939–949.

19. Al-Hamdi, A.M., Dastageer, M.A., Rajeh, A., *et al.,* (2022). Photocatalytic degradation of water disinfection by-products using zirconium doped zinc oxide nanoparticles. *Desalination and Water Treatment*, 252, 339–347.

20. Li, X., *et al.,* (2021). Zirconium-doped zinc oxide nanoparticles as cathode interfacial layers for efficiently rigid and flexible organic solar cells. *The Journal of Physical Chemistry Letters*, 12, 10616–10621.

21. Hassan, M.A., *et al.,* (2017). Effects of rapid thermal annealing on the structural, electrical, and optical properties of Zr-doped ZnO thin films grown by atomic layer deposition. *Materials*, 10.

22. Gouthamsri, S., Ramanaiah, M., Basavaiah, K. and Jaya Rao, K. (2023). Zr-doped ZnO nanohybrid via glycine mediated sol–gel approach as benign supporter for degradation of Crystal violet and antibacterial performance. *Results in Chemistry*, 6, 101080.

23. Nagaraj, K., Kaliyaperumal, R., Poovan, V.K., *et al.,* (2024). Zirconium-doped zinc nanocomposites: Preparation, characterization and evaluation of antibacterial activity. *Journal of Inorganic and Organometallic Polymers and Materials*.

24. *Synthesis of cerium, zirconium, and copper doped zinc oxide nanoparticles as potential biomaterials for tissue engineering applications* (2024). *Heliyon*, 10, e29150.

25. Özgür, Ü., Hofstetter, D. and Morkoç, H. (2010). ZnO devices and applications: A review of current status and future prospects. *Proceedings of the IEEE*, 98, 1255–1268.

26. Carofiglio, M., Barui, S., Cauda, V. and Laurenti, M. (2020). Doped zinc oxide nanoparticles: Synthesis, characterization and potential use in nanomedicine. *Applied Sciences*, 10, 5194.

27. Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N.H.M., Ann, L.C., Bakhori, S.K.M., Hasan, H. and Mohamad, D. (2015). Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. *Nano-Micro Letters*, 7, 219–242.

28. Espitia, P.J.P., Soares, N.F.F., Coimbra, J.S.R., de Andrade, N.J., Cruz, R.S. and Medeiros, E.A.A. (2012). Zinc oxide nanoparticles: Synthesis, antimicrobial activity and food packaging applications. *Food and Bioprocess Technology*, 5, 1447–1464.

29. Raghupathi, K.R., Koodali, R.T. and Manna, A.C. (2011). Size-dependent

bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. *Langmuir*, 27, 4020–4028.

30. Jones, N., Ray, B., Ranjit, K.T. and Manna, A.C. (2008). Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms. *FEMS Microbiology Letters*, 279, 71–76.

31. Janotti, A. and Van de Walle, C.G. (2007). Native point defects in ZnO. *Physical Review B*, 76, 165202.

32. Wang, Z.L. (2004). Zinc oxide nanostructures: Growth, properties and applications. *Journal of Physics: Condensed Matter*, 16, R829–R858.

33. Sahay, P.P., Nath, R.K. and Upadhyay, S.N. (2007). Synthesis of nanocrystalline ZnO particles by sol-gel method. *Journal of Nanoparticle Research*, 9, 201–208.

34. Look, D.C. (2001). Recent advances in ZnO materials and devices. *Materials Science and Engineering: B*, 80, 383–387.

35. Klingshirn, C. (2007). ZnO: Material, physics and applications. *ChemPhysChem*, 8, 782–803.